NATIONAL BUREAU OF STANDARDS REPORT

3556

PROPAGATION ASPECTS OF TACAN SYSTEM COVERAGE

by

Martin T. Decker
National Bureau of Standards
Boulder, Colorado

NBS

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U. S. DEPARTMENT OF COMMERCE
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ABSTRACT

The propagation factors which affect the coverage volume of a TACAN type facility operating in the 1000 Mc region are discussed in this paper. Using theoretical and empirical methods, prediction curves are derived which indicate the probability of receiving satisfactory service in a given volume of air space. Equipment capabilities and interfering co-channel facilities are considered. The coverage volume free from interference is a function of the distance separating co-channel facilities and various spacings are considered, depending on the type of service which a facility might be expected to render.

Included are some of the effects which can be expected from various ground antenna heights, particularly on the interference free coverage volume and on the vertical lobe structure. A number of other factors relating to the ground equipment siting are also discussed.

INTRODUCTION

For the past several years the National Bureau of Standards has been conducting an intensive study of the characteristics of radio propagation in the VHF and UHF ranges, including the TACAN frequency range near 1000 Mc. Experiments performed by the Bureau and other agencies have covered a wide variety of conditions in many parts of the country. Radio field strengths have been measured for extended periods of time over paths both long and short. These data provide a background for predicting the performance of communications systems using these frequencies. The Bureau has been asked to study the propagation aspects of TACAN, in order to answer some of the questions which arise in the implementation of such a system. Primarily the Bureau's responsibility has been the prediction of the coverage which can be expected from the system, considering its capabilities and limitations. Information such as this is important to the implementation of the system in order to know, for example, how many facilities would be required to provide a specified coverage, or to determine how the various frequency channels may be allocated.

There are a large number of factors which affect the air-space coverage of a system such as this, and service in one part of the air-space may have to be sacrificed to obtain better service in another part. The final resolution of the various factors will inevitably be a compromise. Many of the parameters which determine whether satisfactory performance will be obtained by an aircraft are variable and can only be described statistically. Therefore, the final results are in terms of the probability that an aircraft in a particular location will receive service. Operational considerations then dictate how high this probability should be in order for that location to be designated as a part of the coverage volume of the facility. The purpose of this paper is to point out some of these factors, specify their quantitative effects, and comment on their interdependence and relative importance. While the discussions of system performance are based on current production models of the equipment, in nearly all cases the results could be made to apply to any system operating in the 1000 Mc frequency range.

Before going into the actual coverage to be expected from a TACAN facility, comments will be made on some of the individual system parameters. The extent of coverage under typical conditions can then be indicated, and with this coverage as a reference the effect of changes in these initial conditions can be shown.

GROUND REFLECTIONS

The effect of the ground on TACAN system coverage is one of the important things to be considered. It is a well recognized fact that maxima and minima of field strength in the vertical plane are produced at UHF from an antenna located above a good reflecting surface. Low signal areas, or nulls, will exist in those parts of the air-space in which a ray passing directly from the antenna to the aircraft arrives in phase opposition to a ray which has been reflected from the earth. The effect of ground reflection is illustrated in Figure 1. This figure shows a contour of constant signal strength at a frequency of 1100 Mc from an antenna located 18 feet above smooth ground. Field strengths lower than that given by the contour exist at distances outside of the area enclosed; the relatively deep nulls in the pattern are the regions where the direct and ground reflected fields are in phase opposition. It should be noted that the figure is drawn for a perfectly smooth earth - a condition not normally encountered at 1100 Mc.

There are a number of things which may be done to minimize the undesirable effects of these nulls, and they might be divided into two general categories. First, the system might be designed to locate the nulls in a little-used portion of the air-space. An aircraft using a short range navigation system such as TACAN, unless it is very close to the transmitter, will be at a small angle above the horizontal from the transmitting facility. Thus if the first null in this sytem were to be above some angle, such as 10 degrees, it would have little effect on the use of the system. The location of this first null is a function of both the height of the antenna above the reflecting surface and the frequency of transmission. An examination of the quantities involved results in a curve such as that shown in Figure 2. Here it is seen that a scheme such as this may be effective at a frequency of 100 Mc where the required antenna height is about 28 feet. However, the required height at 1000 Mc becomes so small as to be impractical. The system range at angles near the horizon from a facility located at three feet above the ground would not be great.

A second general attack on the problem of nulls is to leave them in the normally used air-space, but reduce their effect in some other way. For example, it may be possible to reduce the magnitude of the energy reflected from the ground (and hence the depth of the null) by using an antenna which discriminates against the energy being directed toward the ground. Such a scheme has been used in the present system

in which the ground antenna has a tilted pattern. Here again the optimum tilt of the antenna is a function of the height above the reflecting surface and the frequency of transmission. If the factors involved here are examined it is found that this approach may be effective at 1000 Mc if the ground antenna height is not too great. If the ground antenna is located as high as 100 feet, however, the optimum tilt is reduced to an angle on the order of 1 or 2 degrees. In this case the reduction of the reflected energy is not great and the scheme becomes ineffective.

Some of the above comments seem to indicate that the lower antenna heights are more advantageous, however, several other factors need to be considered. As the ground antenna height is increased the number of nulls increases with a corresponding decrease in the extent of each individual null. If the nulls are of small extent a time delay or "memory" may possibly be built into the system which is long enough to carry the aircraft through the nulls. Another important observation is an apparent reduction in the effective reflection coefficient as the antenna height is increased. This is due to the fact that the antenna "sees" a larger reflecting surface as the height is increased and the irregularities in this larger surface have a tendency to "break-up" the reflected energy into components having random phase relationship with the direct ray from transmitter to aircraft. This effect tends to reduce the angular width of the vertical nulls. Measurements confirming this observation have been made by several laboratories, including experiments performed by the Bureau of Standards. The assumption of energy in the form of randomly phased reflected rays is used in the prediction curves shown later.

Higher ground antennas may be considered advantageous due not only to this reduction in the angular width of the null, but also for their increased coverage at angles close to the horizon. This latter consideration becomes important in determining the number of facilities which would be required to cover a route or an area down to some minimum altitude.

Balanced against this advantage of greater height are considerations of increased cost of installation, increased losses in connecting cables, greater difficulty of maintenance, and the inability to locate tall structures close to air terminals.

SPACE-WAVE FADEOUTS

The observance of a phenomenon commonly called a space-wave fadeout has been of some concern to agencies contemplating the use of navigation facilities in the UHF range. In general terms, a space-wave fadeout is said to occur when the signal at a receiving location within the radio horizon drops far below its long term median level for an extended period of time. Fadeouts have been described in various publications 1, 2/ but a few of their characteristics could be mentioned here. They vary considerably in depth of fade and in duration. The signal may drop only a few db or as much as 20 db for periods ranging from a few minutes up to several hours. They have been observed in different parts of the country with varying degrees of severity, apparently dependent on the local climatology.

An observation of primary importance is that these fadeouts occur at receiving locations at or just above the radio horizon ray from the transmitter. In this connection an experiment has been performed by the Bureau in which one antenna was located at about 2800 feet above the terrain and the second near the radio horizon of the first. It was found that increasing the height of the second antenna from 5 feet to 43 feet resulted in a significant decrease in the duration and depth of fadeouts. It appears then, that these fadeouts are significant in a rather restricted portion of the air-space. Their effect appears statistically in the work done here as a part of the variability of the signal with time.

AIRBORNE ANTENNA

In order to complete a prediction of system coverage the characteristics of the antennas must be known. The aircraft antenna has been one of the most difficult parameters to describe, since the performance of an antenna varies widely with its type, the type of aircraft on which it is mounted, and its location on that aircraft. A number of directivity patterns of aircraft antennas were analyzed and a composite "typical antenna" was described statistically. Thus there is a probability of realizing a given antenna gain at any azimuth angle and at any angle above or below the horizontal plane through the aircraft. The absolute gain of the antenna was taken to be a function of this angle relative to the horizontal. Most of the antennas considered were belly antennas and the maximum gain was found to be at about 10 degrees below the horizontal. The median gain at this point is 4.5 db over an isotropic radiator, decreasing to about 2 db at the horizontal. This

means that in this study we have a probability of 0.5 of realizing dipole gain in the horizontal direction.

GROUND ANTENNA

The pattern of the ground antenna has been taken from measurements of typical production models of the URN-3. The maximum gain of this antenna in the vertical plane occurs at about 7 degrees above the horizontal and the value used is 6 db over a dipole at this point.

COVERAGE CALCULATIONS

We may now turn to the methods employed in predicting the extent of the air-space which can be served by a single TACAN facility. It has been found convenient in these calculations to employ a term known as "transmission loss", which is defined as the ratio of power supplied to the terminals of a loss-free transmitting antenna to the power available at the terminals of a loss-free receiving antenna, expressed in decibels. Or in simpler terms, it is the loss in energy which results from the fact that the two antennas are separated in space. This procedure has the advantage that system characteristics such as transmitter power, receiver sensitivity, and losses in connecting transmission lines need not enter the calculation of transmission loss. The characteristics of the transmitting and receiving antennas are, however, included in the initial calculation.

Two regions of space have been considered in the calculation of transmission loss. The first of these is the air-space within the radio horizon, and the second the space beyond the radio horizon. Methods have been developed which work quite well for predicting transmission loss for points well within this horizon and for points well beyond the horizon, while the region near the horizon is more difficult to handle. Due to the variation of radio wave refraction in the atmosphere there is no sharp boundary between these two regions. The curves obtained for the one region are blended with those for the other, and a smooth curve of transmission loss versus distance may be plotted for any combination of antenna heights.

WITHIN RADIO HORIZON CALCULATIONS

For points within the radio horizon the field at the aircraft was assumed to be made up of (1) a ray passing directly from the transmitter to the aircraft, having free space attenuation, and (2) a

reflection considered to be a large number of rays arriving at the aircraft in random phase relationship to the direct ray. The energy contained in this reflection relative to the energy in the direct ray is determined by the vertical directivity of the ground antenna and by the proportion of the incident energy actually reflected from the ground. This latter proportion is the effective reflection coefficient mentioned earlier. The resulting field intensity (or transmission loss) then becomes the vector sum of a steady component plus a Rayleigh distributed varying component. The form of the resulting distribution of signal levels has been investigated at the Bureau of Standards and the results published in a recent paper 3/. It is found that the form of this distribution is a function of the relative powers in the constant and the varying components.

We have so far mentioned three factors which contribute to the variability of transmission loss, namely the aircraft antenna, the randomly phased ground reflection, and the time variability of the transmission loss determined by long term propagation measurements. These three factors are combined to arrive at a graph showing the cumulative probability distribution of the transmission loss at any point within the radio horizon.

BEYOND RADIO HORIZON CALCULATIONS

The calculations have been extended to points beyond the radio horizon in order to have information for interference estimates. Empirical curves derived from propagation measurements at distances beyond the radio horizon have been used. From these data the median transmission loss can be determined for points beyond the radio horizon and for various combinations of transmitting and receiving antenna heights. To these median values of transmission loss have been added the variability to be expected from long term time variations, again derived from measurements at 1000 Mc. This latter variation, incidentally, is greatest at a short distance beyond the radio horizon. In addition, the variability due to the statistically described "typical aircraft antenna" was combined with the above distribution of transmission loss. The data derived here were then interpolated through the region of the radio horizon with the calculations which were made for propagation within the horizon, providing a continuous prediction of transmission loss for any distance and for a selected number of aircraft altitudes.

COMPARISON OF CALCULATED AND MEASURED DATA

Figure 3 indicates typical results obtained from the foregoing methods, and shows a comparison with actual data. The sample calculation illustrates the transmission loss to be expected along the Bureau of Standards' Cheyenne Mountain path at 1046 Mc by an aircraft at 15,000 feet above sea level. The transmission loss is expected to be within any part of the shaded area with a probability of 0.998, and within the heavily shaded area with a probability of 0.90. The aircraft antenna used in the experiment was not a typical operational antenna, but was a directional antenna oriented toward the transmitting source. For this reason the variability associated with operational antennas has not been included.

The dashed line is the transmission loss actually measured by an aircraft on a single flight along this path. Since the measured data are from a single flight, they would not be expected to contain long term time variations.

MAXIMUM ALLOWABLE TRANSMISSION LOSS

Since the prediction curves have been calculated in terms of transmission loss as described earlier, it now becomes a simple matter to describe the performance of the system under any of a large variety of conditions. For the system under consideration a quantity which is called maximum allowable transmission loss may be determined. This quantity is a function of the power supplied by the transmitter, all power losses in transmission lines, antennas, and mismatching, the gains of transmitting and receiving antennas, and the sensitivity of the receiver. All these quantities are combined to determine what transmission loss may be tolerated and still have satisfactory operation of the system. It is also a simple matter to determine the effect of changing any of the parameters mentioned.

The maximum allowable transmission loss as determined by the ground-to-air parameters appears to be the limiting case in the TACAN system. The air-to-ground transmission is therefore not considered in this paper.

COVERAGE WITHOUT CO-CHANNEL INTERFERENCE

Taking as typical values for the above factors a transmitter power of 5 KW, receiver sensitivity of -85 dbm, line losses of 6 db,

and antennas as discussed earlier, we arrive at a maximum allowable transmission loss of 146 db. The coverage to be expected from a 100 foot ground antenna tower is shown in Figure 4. The air-space within each curve would be expected to have service with at least the probability indicated.

The probabilities shown in the diagrams in this paper do not include an analysis of equipment reliability.

If the maximum allowable transmission loss is decreased, for example, by the use of a poorer aircraft antenna, or by a decrease in the sensitivity of the receiver, the coverage would be affected as shown in Figures 5 and 6. Here are graphs similar to that in Figure 4, except that the maximum allowable transmission loss has been decreased by 6 and 12 db.

COVERAGE IN THE PRESENCE OF INTERFERENCE

Up to this point performance has been considered as if we had only a single isolated facility. Obviously, there will be other facilities and some of them must be operated on the same channel assignment as that designated for our first facility. So the performance of the system in the presence of co-channel interference must be considered. The volume of air-space that a given facility is to serve depends on how it is to be used. For example, the use of a facility by an aircraft on a long distance flight might require the full range capabilities of the system, and there could be no interference from other facilities for this full range. On the other hand a facility might be required to provide aid for an aircraft only in its approach to a terminal and so needs to give service to a much shorter range. In the second case a much smaller spacing of co-channels can be tolerated. For this reason various co-channel spacings have been considered.

In order for a facility to provide service in the presence of interference, the received signal must exceed a combination of (1) the minimum detectable signal, and (2) the interfering signal plus a protection ratio. Lines of constant probability that the desired signal will exceed this combination have been determined for various conditions of ground antenna heights and co-channel spacings.

Figures 7, 8, and 9 show examples of the coverage to be expected in the vertical plane containing the desired and undesired co-channel facilities, each at 100 feet above the terrain. The assumption is made

that the desired signal must be at least 12 db greater than the undesired. In each case interference limits the service at higher altitudes while lack of sufficient signal strength is limiting at lower altitudes.

The effect of increasing the transmitting antenna height above 100 feet has been examined with a 300 nautical mile station separation. If both antennas are raised to 200 feet there will be practically no change in the service at the higher altitudes. Service range at the lower altitudes will be increased by about 5 miles. This indicates that doubling the height of a 100 foot tower would be of value only to low flying aircraft provided that the 100 foot tower is clear of nearby obstructions.

The effect of elevating the interfering facility to 2000 feet is shown in Figure 10. This might be possible if one facility were located on a mountain top. Again the separation of stations is 300 nautical miles and the desired facility is 100 feet above the terrain. Here the service from the desired facility is reduced, particularly at the higher altitudes.

Figure 11 indicates the approximate co-channel separation which is required for 100 foot facilities if the facilities are to be used to the full 200 mile range for which they were designed.

REFERENCES

1/ A. P. Barsis, B. R. Bean, J. W. Herbstreit, K. O. Hornberg, and K. A. Norton, "Propagation of Radio Waves Over Land at 1046 Mc", National Bureau of Standards Report No. 2494, May 1953.

2/ Bradford R. Bean, "Prolonged Space-wave Fadeouts at 1046 Mc Observed in Cheyenne Mountain Propagation Program," Proceedings of the IRE, Vol. 42, No. 5, May 1954.

3/ K. A. Norton, L. E. Vogler, W. V. Mansfield, and P. J. Short, "The Probability Distribution of the Amplitude of a Constant Vector Plus a Rayleigh-Distributed Vector," Proceedings of the IRE, Vol. 43, No. 10, October, 1955.

THEORETICAL RADIATION PATTERN FOR A TACAN ANTENNA LOCATED 18 FEET ABOVE A SMOOTH SPHERICAL EARTH

Not To Be Expected Over Actual Rough Earth

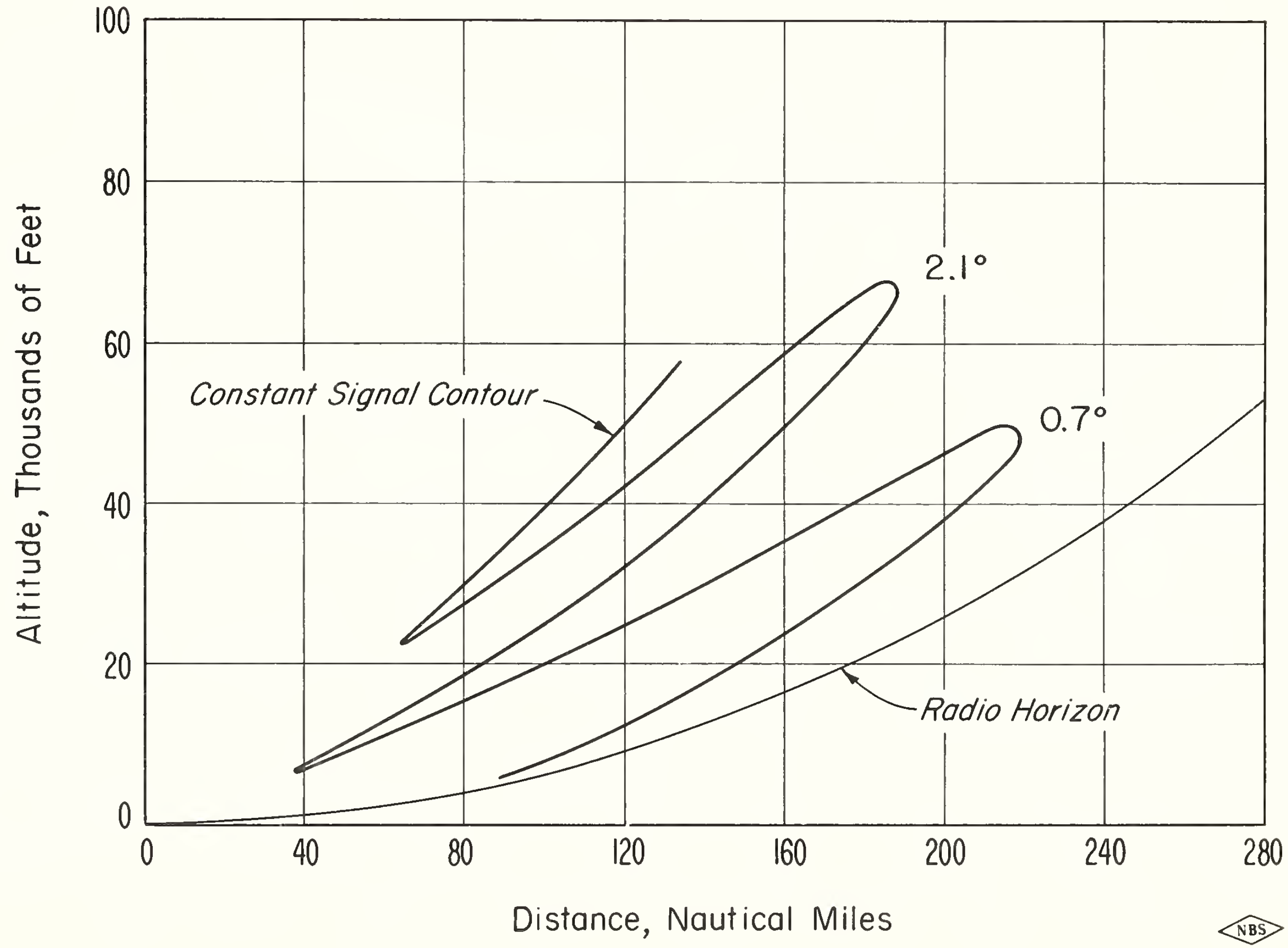

Figure 1

REQUIRED GROUND ANTENNA HEIGHT FOR FIRST VERTICAL NULL TO BE AT 10 DEGREES ABOVE THE HORIZONTAL

Smooth Spherical Earth; Standard Atmosphere

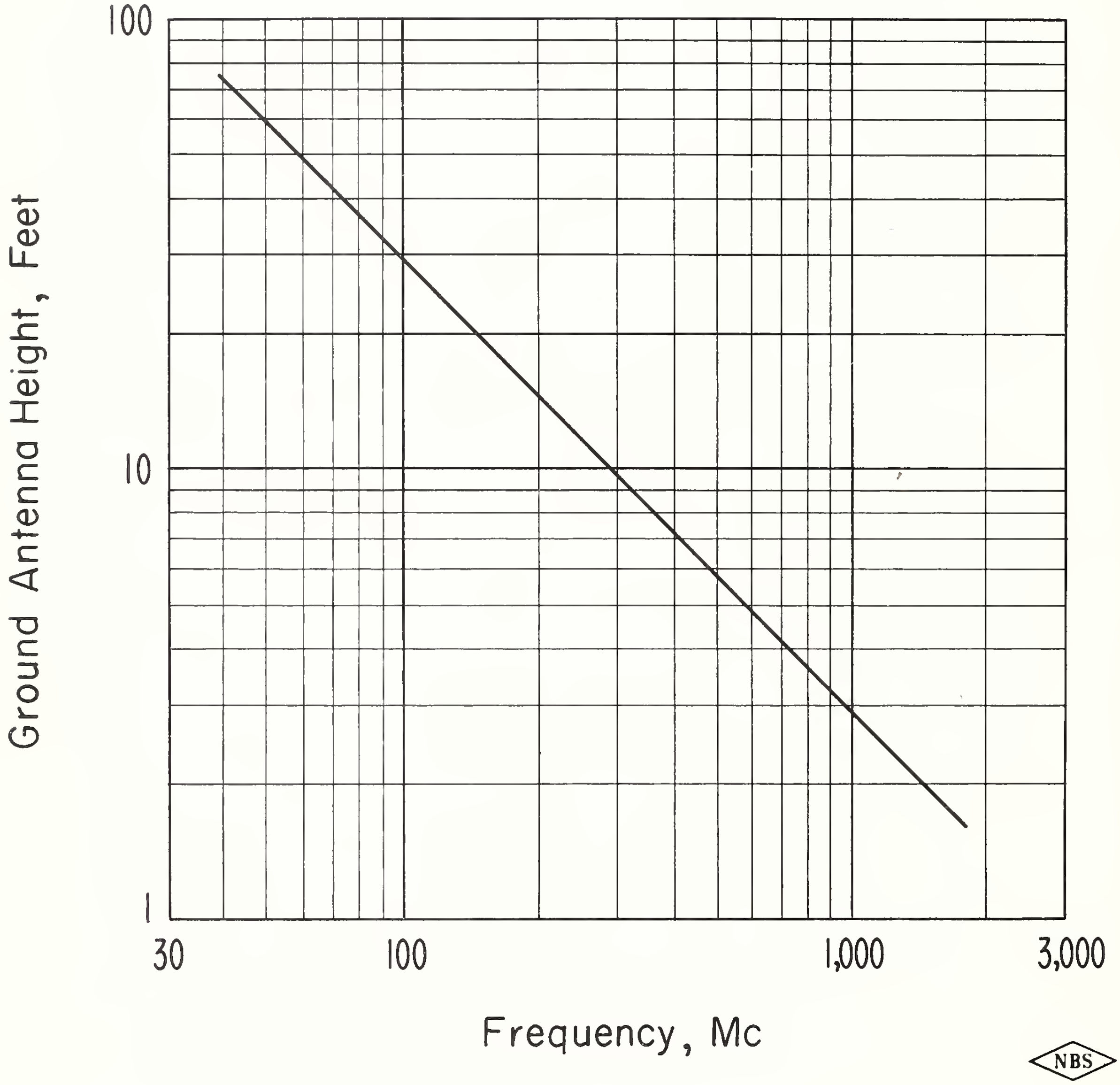

Figure 2

COMPARISON OF MEASURED AND CALCULATED TRANSMISSION LOSS

Cheyenne Mountain Path; 1046 Mc; Antenna Height 2,800 Feet
Aircraft Altitude 15,000 Feet

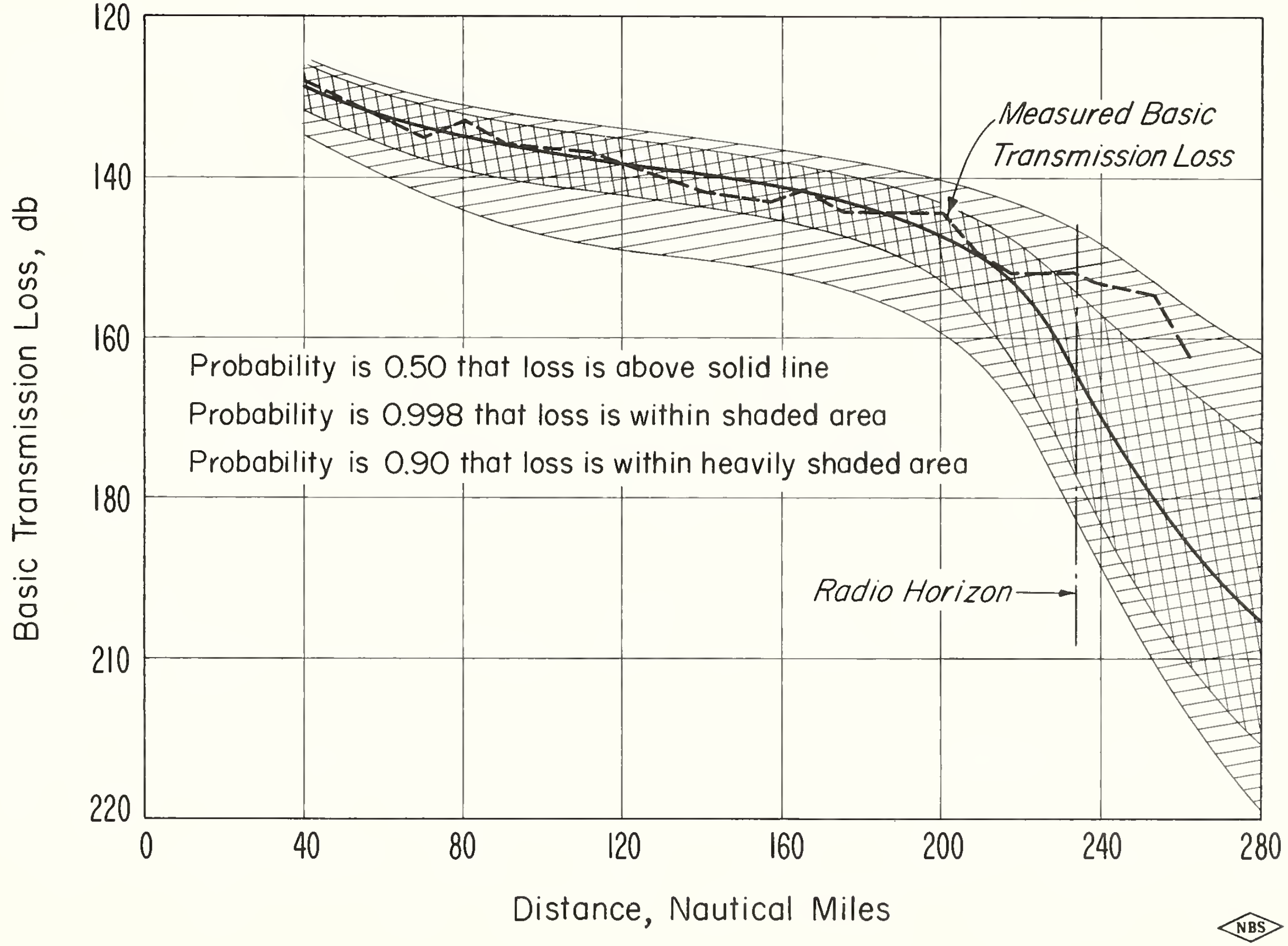

Figure 3

PROBABILITY OF SERVICE FROM A TACAN FACILITY
NO INTERFERING FACILITIES

Maximum Allowable Transmission Loss 146 db
Antenna Height 100 Feet

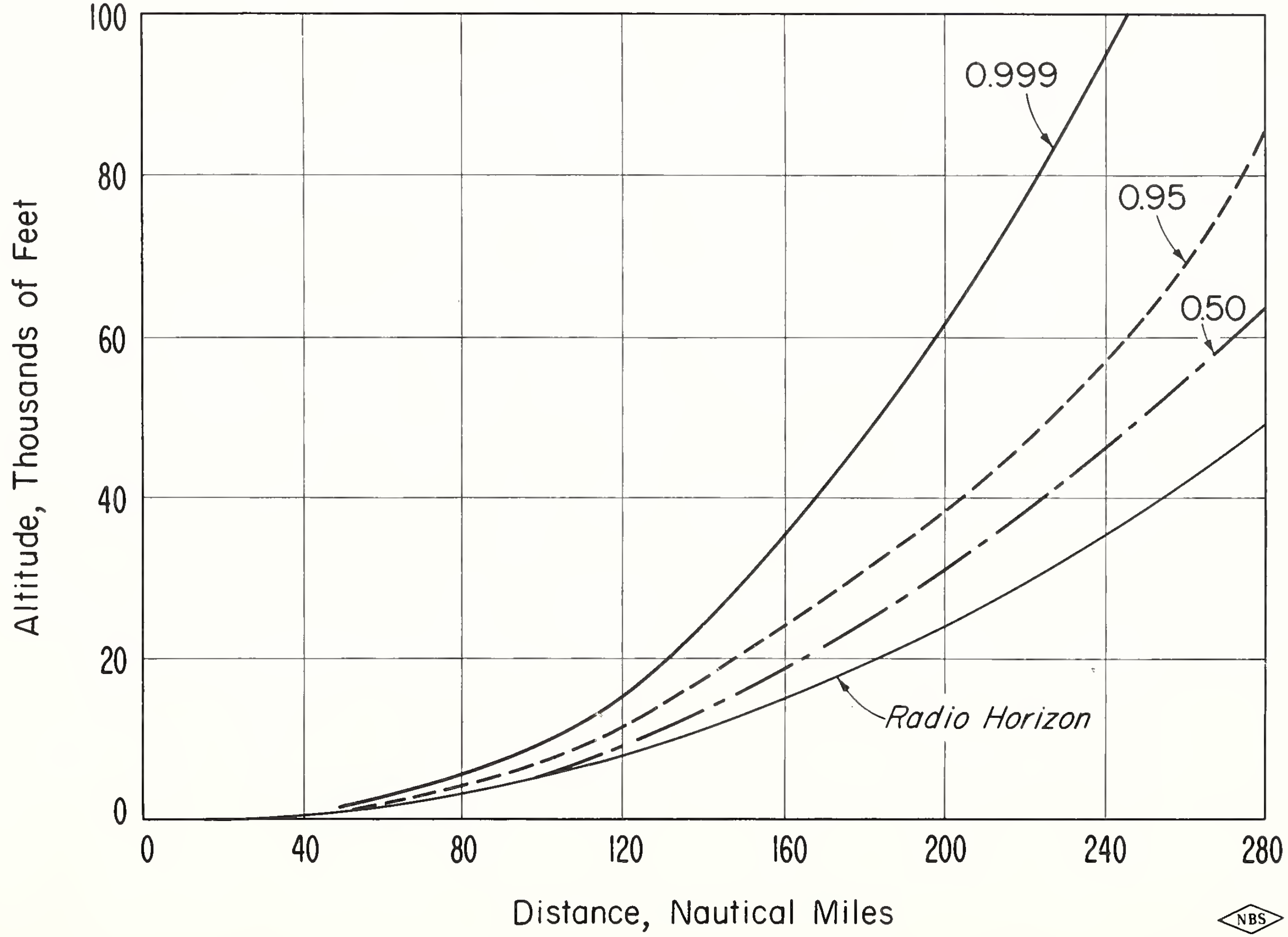

Figure 4

PROBABILITY OF SERVICE FROM A TACAN FACILITY
NO INTERFERING FACILITIES

Maximum Allowable Transmission Loss 140 db
Antenna Height 100 Feet

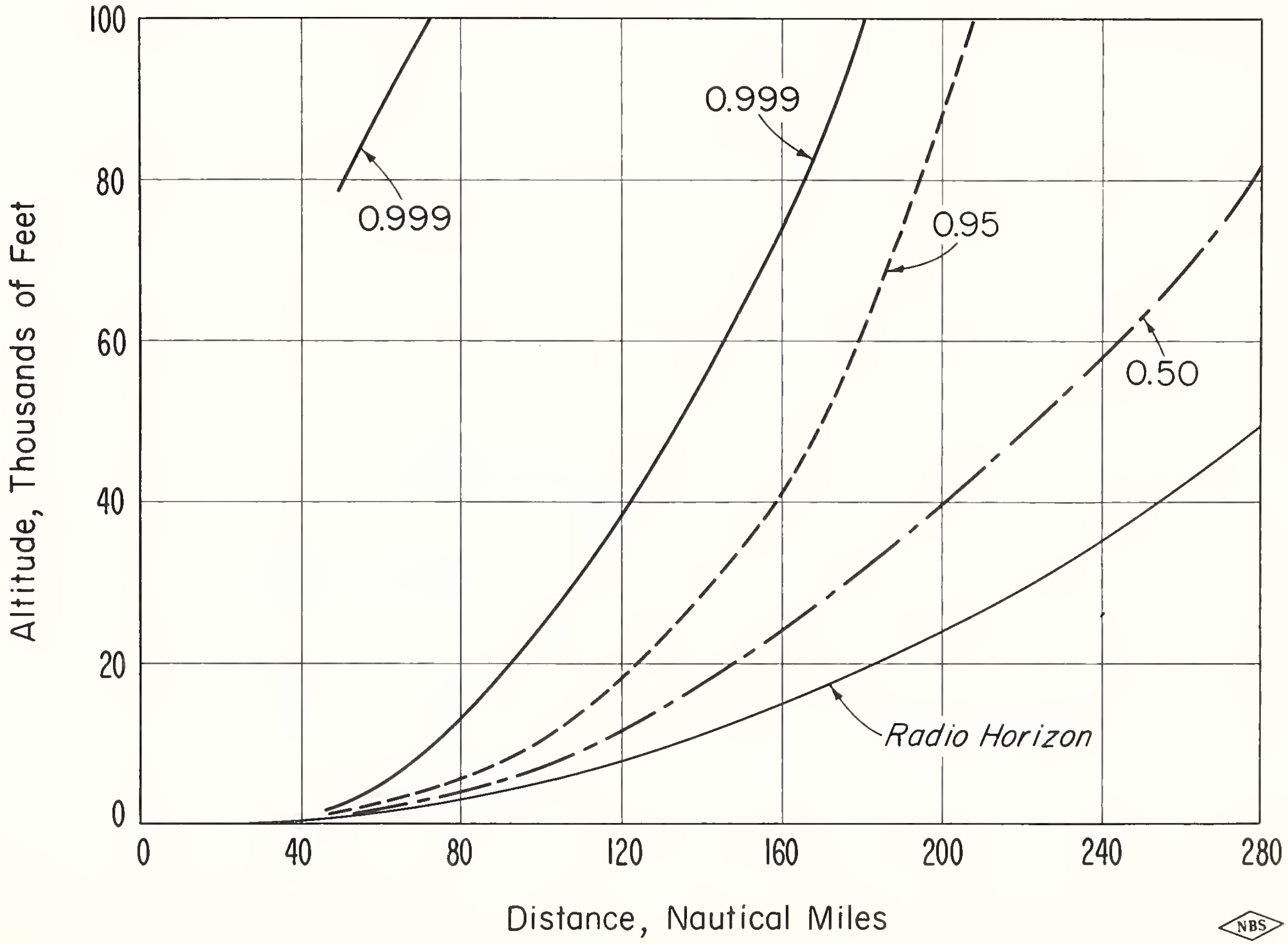

Figure 5

PROBABILITY OF SERVICE FROM A TACAN FACILITY
NO INTERFERING FACILITIES

Maximum Allowable Transmission Loss 134 db
Antenna Height 100 Feet

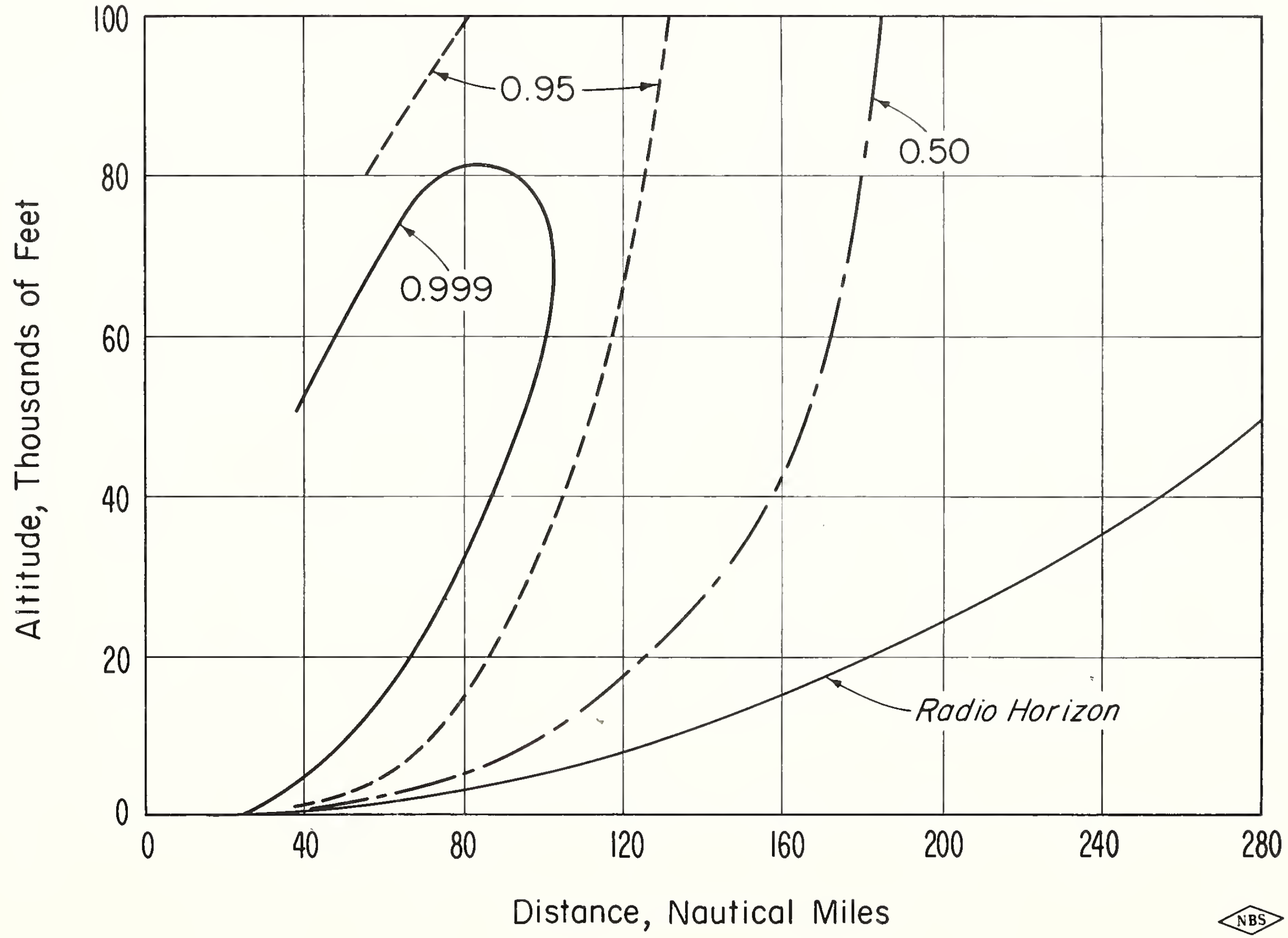

Figure 6

PROBABILITY OF SERVICE FROM A TACAN FACILITY
ONE CO-CHANNEL INTERFERING FACILITY

Co-Channel Separation 150 NM; Maximum Allowable Transmission Loss 146 db
Protection Ratio 12 db; Antenna Height 100 Feet

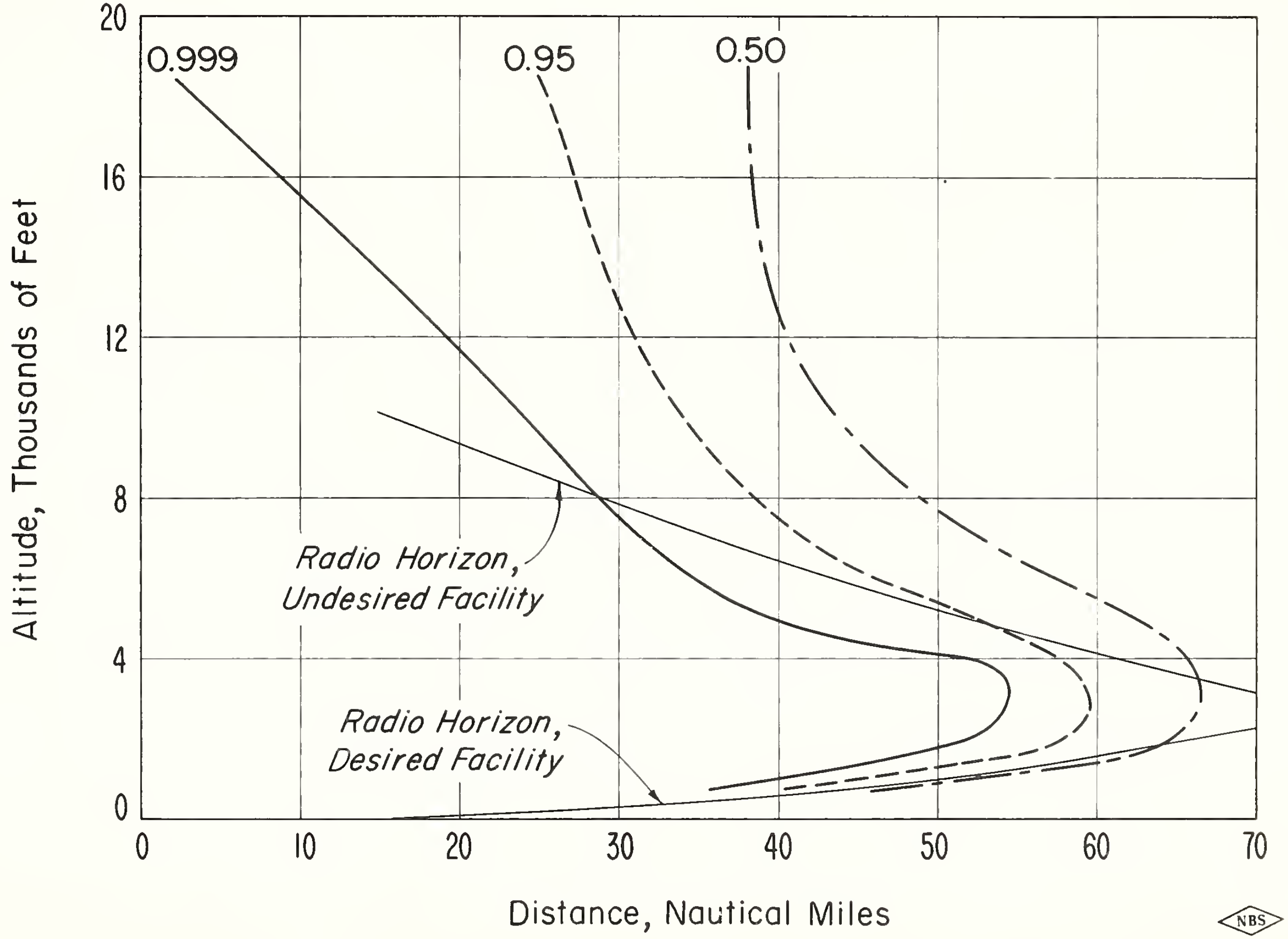

Figure 7

PROBABILITY OF SERVICE FROM A TACAN FACILITY
ONE CO-CHANNEL INTERFERING FACILITY

Co-Channel Separation 250 NM; Maximum Allowable Transmission Loss 146 db
Protection Ratio 12 db; Antenna Height 100 Feet

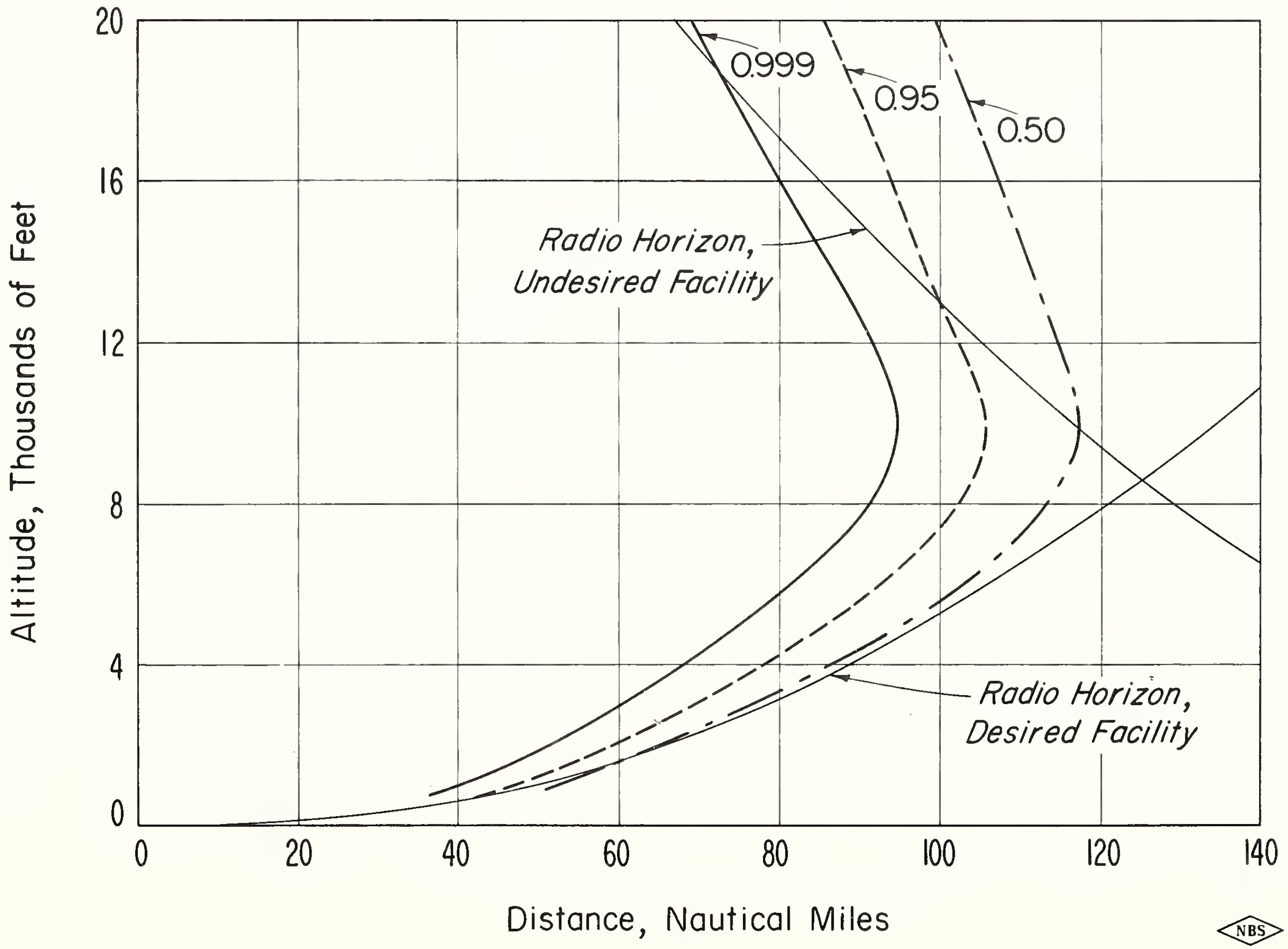

Figure 8

PROBABILITY OF SERVICE FROM A TACAN FACILITY
ONE CO-CHANNEL INTERFERING FACILITY

Co-Channel Separation 300 N M; Maximum Allowable Transmission Loss 146 db
Protection Ratio 12 db; Antenna Height 100 Feet

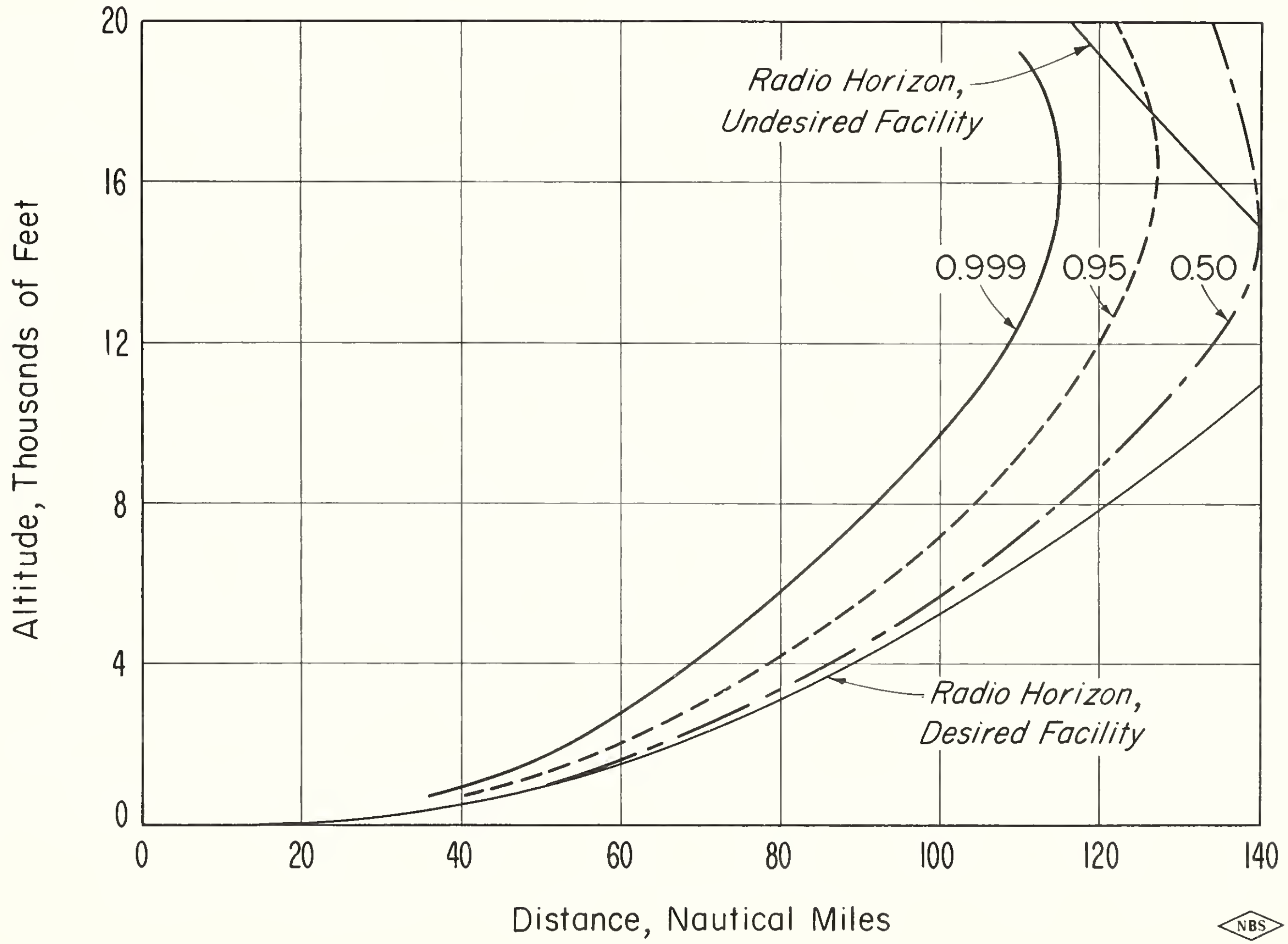

Figure 9

PROBABILITY OF SERVICE FROM A TACAN FACILITY
ONE CO-CHANNEL INTERFERING FACILITY

Co-Channel Separation 300 NM; Maximum Allowable Transmission Loss 146 db
Protection Ratio 12 db
Antenna Height: Desired Facility 100 Feet; Undesired Facility 2,000 Feet

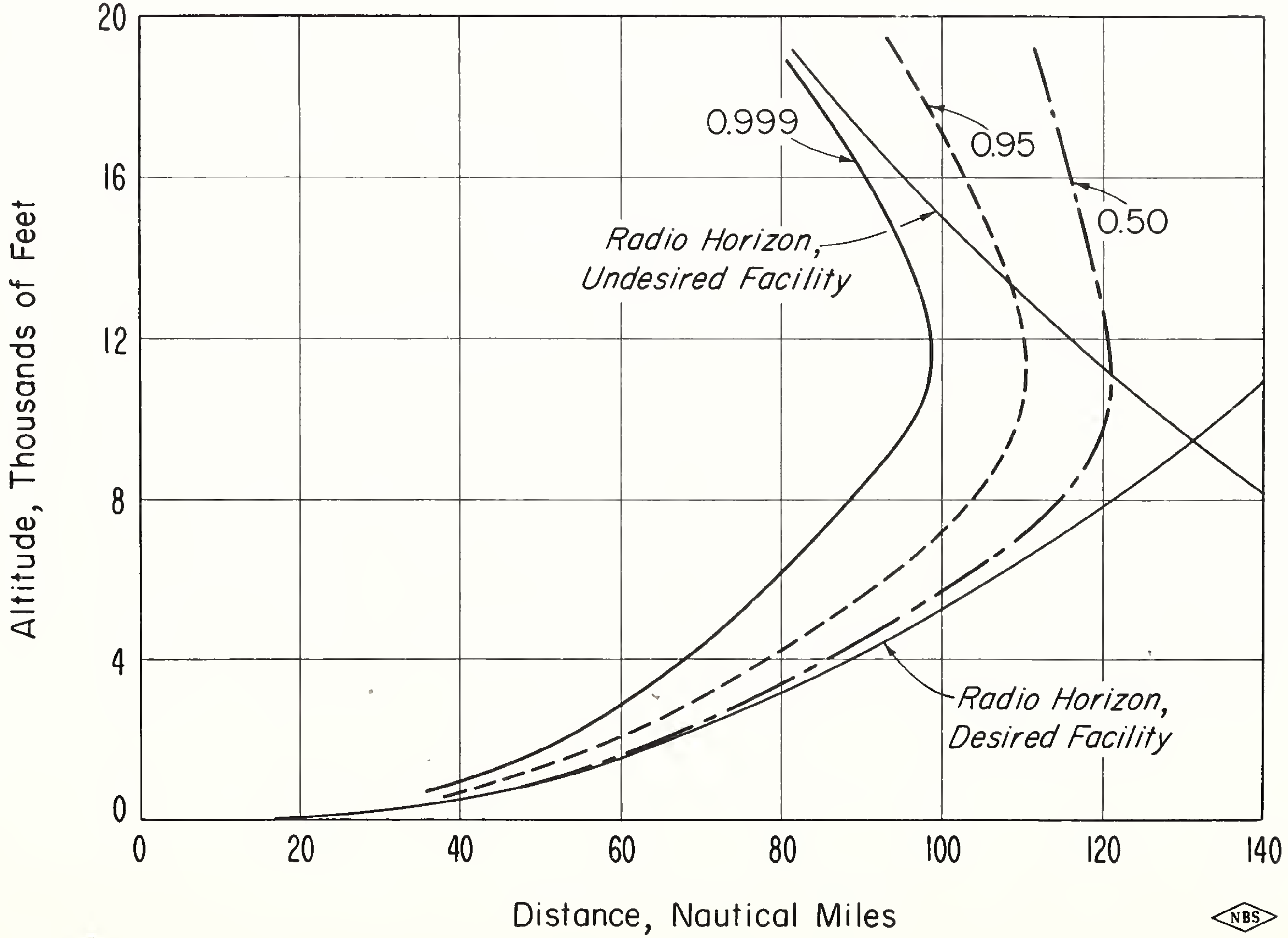

Figure 10

PROBABILITY OF SERVICE FROM A TACAN FACILITY
ONE CO-CHANNEL INTERFERING FACILITY

Co-Channel Separation 550 NM; Maximum Allowable Transmission Loss 146 db
Protection Ratio 12 db; Antenna Height 100 Feet

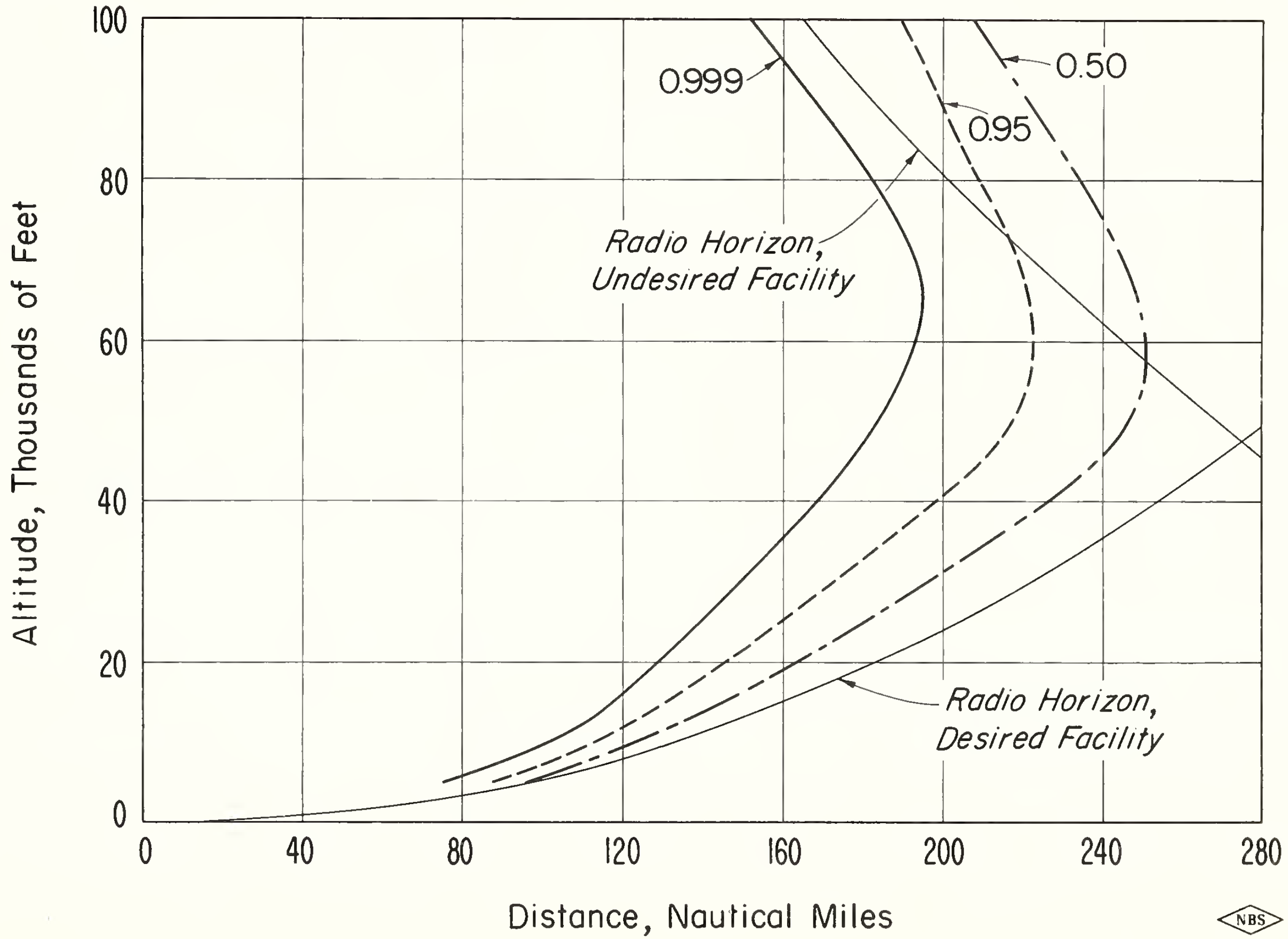

Figure 11

THE NATIONAL BUREAU OF STANDARDS

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The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to Government Agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. A major portion of the Bureau's work is performed for other Government Agencies, particularly the Department of Defense and the Atomic Energy Commission. The scope of activities is suggested by the listing of divisions and sections on the inside of the front cover.

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